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Plasma Observations in the Auroral and Polar Cap Region

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15 December 1985

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The last decade has seen a period of rapid growth in our understanding of the processes which occur in the auroral regions. Much of our understanding is based on the copious new observations which have been made available in the auroral community. The present work is a short overview of the plasma conditions which obtain throughout much of the auroral region. It covers the diffuse and discrete auroral electron precipitation in the morning and evening oval, cusp, and polar cap. The ionospheric ion outflow throughout the high latitude regime is also described and related to the electron observations.

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PREFACE

The author would like to thank Drs. Y. T. Chiu, D. J. Gorney, L. R. Lyons and P. F. Mizera for many useful discussions.

CONTENTS

FIGURES

1. INTRODUCTION

This overview will attempt to summarize our present knowledge of the plasma distributions which obtain in the auroral and polar cap regions. As such, little will be said about the theory of auroral plasmas. The intent is to present a reference description of the plasma regime that the theory and simulations must contend with. Given the shortness of this report, the topics are not covered in detail. A fairly detailed reference list has been included so that the reader can easily find the most recent and detailed information. The report treats the electron observations first (Section 2) and then the ion observations (Section 3). Each major section is broken down into subsections with the electron subsections covering the different auroral regions according to local time and latitude and type of precipitation. The ion section emphasizes ionospheric ion outflow and distinguishes between the energetic and polar wind ion outflow. The energetic ion outflow discussion is further divided into sections on conics and field-aligned beams.

2. ELECTRON PRECIPITATION

2.1 DIFFUSE AURORA

The diffuse aurora appears as a broad band of weak auroral luminosity extending around the auroral zone. Simultaneous observations of the diffuse auroral precipitation and the equatorial central plasma sheet fluxes show that the central plasma sheet is the source of the precipitating particles. No acceleration is required to cause the spectral characteristics of the central plasma sheet and auroral precipitation to match. Meng et al. (1979) found good agreement between the spectral shapes in the two regions, as is shown in Figure 1. The electron intensities were similar. They concluded that the precipitation did not require a potential drop, only pitch angle transport.

The equatorward edge of the diffuse aurora generally maps to the inner edge of the plasma sheet (Horwitz et al., 1982; Gussenhoven et al., 1983). This requires that pitch-angle scattering processes are acting to continuously dump electrons into the loss cone throughout the central plasma sheet region and down to the innermost edge of the plasma sheet. It is speculated that the wave particle interaction which caused the electron precipitation is at the strong scattering limit.

Fairfield and Viñas (1984) have argued that the plasma sheet electrons are frequently not in strong diffusion. They and others (e.g., Ashour-Abdalla and Thorne, 1978) have noted that the anisotropies resulting from single particle motion in the outer magnetosphere are the most likely source of free energy for the waves which precipitate the electrons. Belmont et al. (1983) argue that the observed electrostatic cyclotron harmonic wave amplitudes in the equatorial plasma sheet seldom reach the levels required to cause strong pitch angle scattering. They suggest that other mechanisms may play important roles in generating the electron precipitation from the plasma sheet required to generate the diffuse aurora.

Thus we are left with the impression that the current wisdom concerning the source and mechanism for generating the electron precipitation for the diffuse aurora is generally correct but some questions concerning the details remain. For example, is strong pitch angle diffusion required to provide the precipitating electron fluences observed at low altitude or are the observed

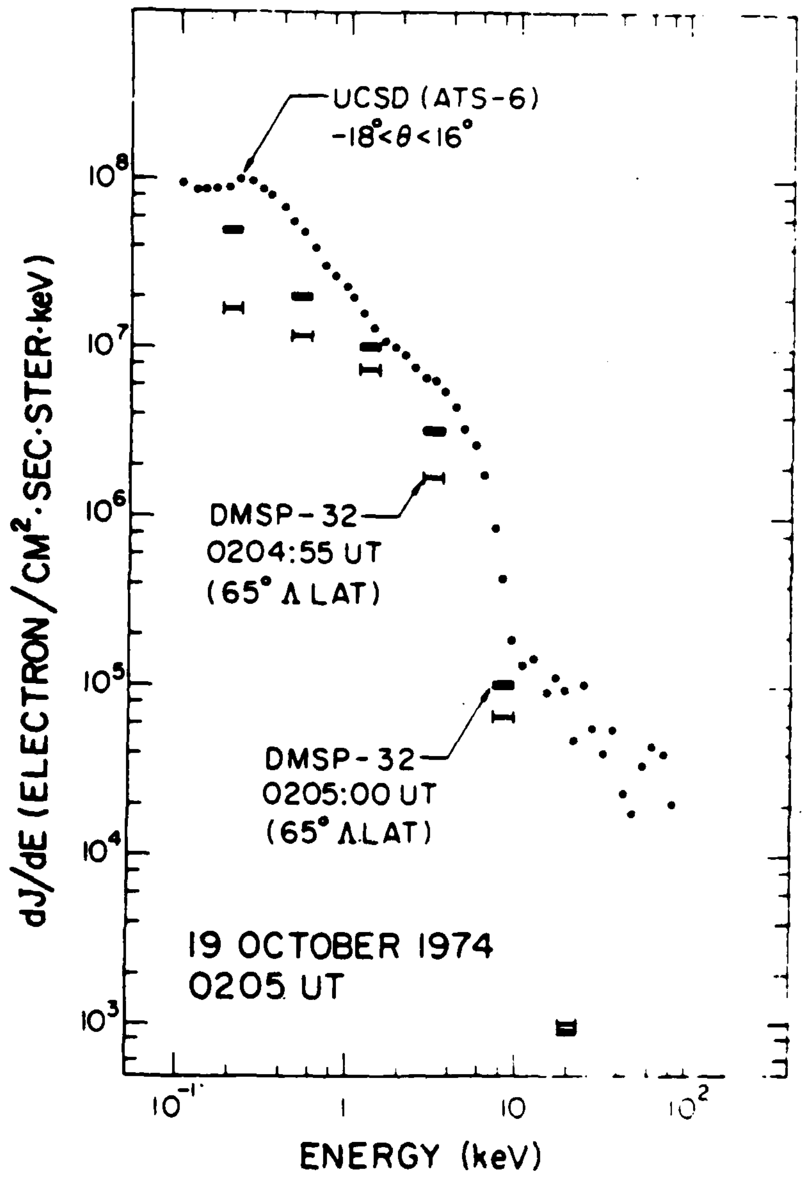

Figure 1. Coordinated Observation of Plasma Sheet Electrons at Geosynchronous Orbit by ATS-6 and the Diffuse Aurora Electron Precipitation at Low Altitudes Near the Conjugate Field Lines by DMSP-32 (after Meng et al., 1979).

wave amplitudes and spatial distributions consistent with those required to supply the precipitation?

2.2 NIGHT SIDE PRECIPITATION

The nightside auroral arc precipitation is dominated by discrete arc precipitation and 'inverted-V' precipitation regions combined with the diffuse aurora precipitation (Akasofu and Kan, 1980; Reiff, 1983). The discrete arc and 'inverted-V' precipitations show signatures of field-aligned acceleration of plasma sheet electrons by 'parallel' electric fields (see Burke, 1982; Reiff, 1983; Fennell, 1985 and references therein). The 'inverted-V' structures span the range of latitudinal scale lengths from ~ 0.2° to 3° and have a mean width of ~ 0.5° in invariant latitude (Lin and Hoffman, 1982 and references therein). These are wider than discrete arcs or electrostatic shocks. Generally, the inverted-V region also corresponds to a region of accelerated ion outflow (see Sec. 3) and intense wave turbulence (Mozer et al., 1980). Sometimes the inverted-Vs have embedded in them bursts of intense electron precipitation associated with the electrostatic shocks (Lin and Hoffman, 1979b; Mizera et al., 1981).

The kinds of particle distribution functions seen in the nightside auroral zones have been summarized by several authors (see Fennell, 1984 and references therein). Examples of these distribution functions are shown in Figure 2a. Basically, at satellite altitudes the inverted-V electrons show the peaked energy spectra indicative of a potential drop existing at $\geq$ few thousand km altitude on the field line. In rare instances the inverted-V signature has been seen at very high altitudes (~ 13 R_e, Huang et al., 1984). If the inverted-V observations are in the acceleration region, as is the case in Figure 2a, the resulting enhanced loss cone, field-aligned beam and a "trapped" component of the electrons are observed (see Chiu et al., 1983a and references therein). This indicates that the particle motion is sufficiently adiabatic at the observation altitude to maintain signatures of the forces which are acting on the particles. These signatures are not always maintained down to low (few hundred kilometers) altitudes. Often at low altitudes the particle distributions have been much smoothed by scattering processes and at very low altitudes by the interaction with the topside of the atmosphere (Pulliam et al., 1981; Prasad et al., 1983).

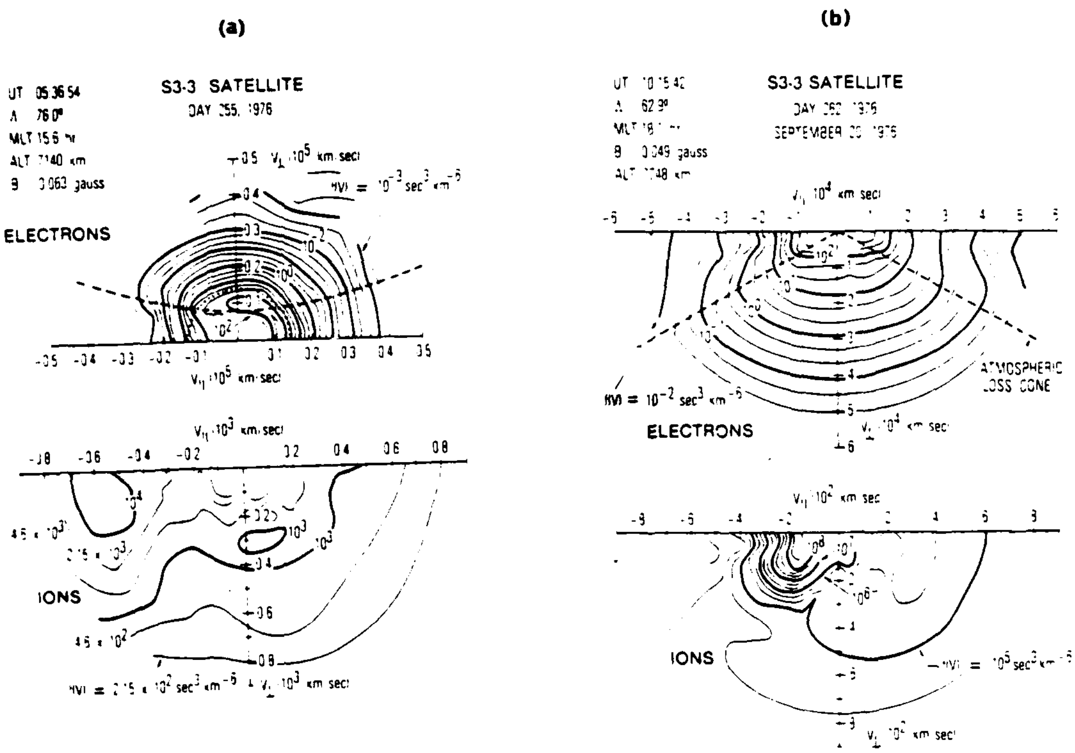

Figure 2. Typical Electron and Ion Distribution Functions Observed in Inverted-V Regions (a) and in the Return Current Region (b). The electron and ion distribution in (a) are consistent with a potential drop of 0.5 kV above and 2.2 kV below the observation altitude. Panel (b) shows the simultaneous occurrence of bidirectional electron beams and ion conics (after Chiu et al., 1983).

The electron distribution functions measured in the inverted-V regions are generally consistent with the picture presented by Evans (1974) in which a hot Maxwellian source distribution is assumed to fall through a potential drop and interact with the atmosphere producing secondaries and degraded primaries. The upgoing secondaries and primaries, with energies less than the potential barrier, are reflected downward to interact with the atmosphere again (see Pulliam et al., 1981).

One question which is often asked is how stable is the inverted-V acceleration process? Auroral arcs are known to persist for tens of minutes, based on photographic studies (see Reiff, 1983). But it is very difficult to determine whether the spatial and temporal character of the precipitating electron spectra remains stable for such periods. Rocket flights are too short and the time between successive polar traversals by a satellite is too long. It is known that the altitudinal distribution of the potential drop varies within an inverted-V (see Fig. 6 of Fennell et al., 1981). It is not known whether this distribution is time-stationary. Using the recent combined DE-1 and -2 coplanar observations, Thieman and Hoffman (1985) argue that inverted-Vs can remain reasonably stable for at least a few minutes and up to 18 minutes. At this point in time there is no satisfactory answer to the stability question.

There is a relatively large collection of plasma observations, taken predominantly in the nightside auroral region, which do not appear to fit the simple Evans (1974) picture. For example, intense field-aligned electrons with steep, unpeaked energy spectra are often observed at the edges of inverted-Vs usually at lower altitudes (Bryant, 1978; Wahlen and Daly, 1979; Fennell et al., 1981, Collin et al., 1982; Bryant, 1983). Also, at times the inverted-V precipitating electrons just below the peak of the energy spectrum are field-aligned, not isotropic, as is expected for secondary electrons. Thus it is argued they are primary downgoing particles (see Bryant, 1983). Finally, there are double peaked inverted-V precipitating electron energy spectra (Hoffman and Lin, 1981; Arnoldy, 1981). Examples of both of these latter characteristics are shown in Figure 3. These data were taken at relatively low altitudes. Generally, wave-particle interactions are called upon to explain such auroral electron distributions (Lin and Hoffman, 1979b; Bryant, 1983; Bingham et al., 1984; and references therein). When the wave observations are examined it is often found that the waves do not carry enough

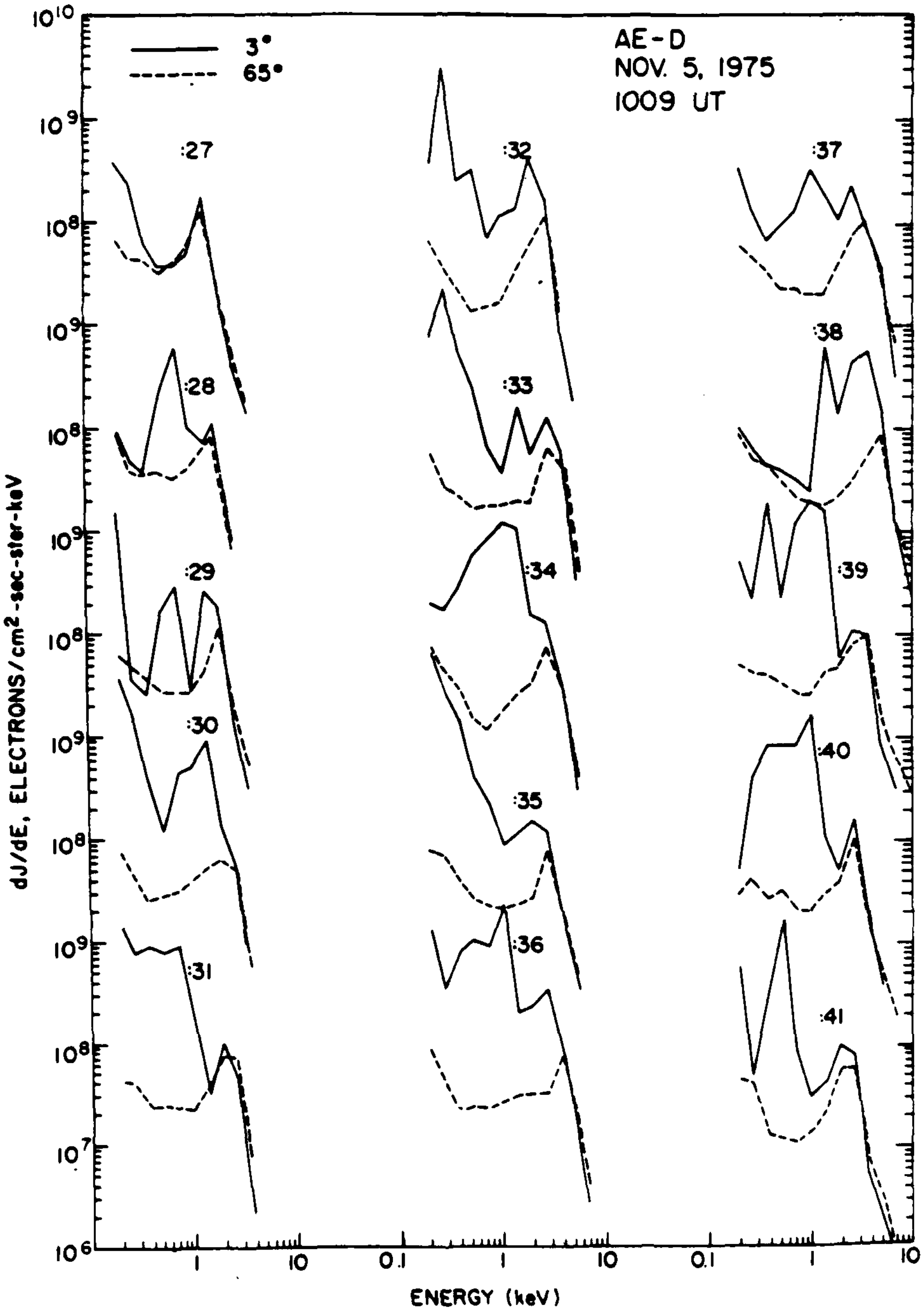

Figure 3. Energy Spectra Showing Multiple Peaks and Strong Field Alignment of the Low Energy Component of Inverted-V Electron Precipitation (after Lin and Hoffman, 1979).

energy to provide the necessary acceleration (Gurnett and Frank, 1977) to explain such particle observations. Part of the difficulty lies with insufficient simultaneous high-resolution wave and particle data. Thus we are left with a set of nightside auroral observations for which there are no generally accepted explanations.

The general picture for the nightside that one gets from examining the wealth of precipitating electron data available and the DC and AC electric field results is: the narrow discrete auroral arcs correspond to the intense latitudinally narrow regions of electron precipitation and the broader 'arcs' correspond to the inverted-V precipitation. The narrow arcs may correspond with electrostatic shocks. At least, the shock scale lengths are comparable to that of the narrow arcs. Recently, Kletzing et al. (1983) has shown evidence that the electrostatic shocks are indeed correlated to discrete arcs.

2.3 MORNING SIDE AURORA

The morning side aurora appears to be a relatively broad region of emission composed of different forms. There are the rare higher latitude arcs which often extend from the dayside or nightside (Akasofu and Kan, 1980; Akasofu, 1981) and which are caused by relatively soft and structured electron precipitations. The source region electron spectra of the high latitude arc precipitation can be characterized as magnetosheath or boundary-plasma-sheet-like. There are also the hard precipitating electrons at lower latitudes, which are usually uniform but can take a structured appearance at the recovery phase of the substorms. The recovery is often associated with the hard and intense mantle aurora precipitation which spreads through local morning from the nightside (Hoffman and Burch, 1973; Meng and Akasofu, 1983). Often these low-latitude precipitations are patchy in nature. The patches are often associated with pulsations (Johnstone, 1978; Roywick and Davis, 1977). Although the morning discrete arcs are rare, when they occur they appear, optically, much as other discrete arcs. Of course, the diffuse auroral precipitation also occurs on the morning side.

Because the morning side also contains the pulsating aurora it has been the focus of investigations to understand how the pulsating electron precipitation is generated (Berkey, 1980; Sandahl et al., 1980; Sandahl, 1984). There is evidence that these pulsating aurora undergo E x B drift motion

(Scourfield et al., 1983) and drift with the background plasma. Many of the features of pulsating aurora have been summarized by Roywik and Davis (1977) and in Sandahl's (1984) thesis. It is known to occur, typically, at the recovery phase of substorms. The variation of the electron precipitation tends to be only at the higher energies (> few keV and extending to many tens of keV). An example of the electron spectra at the maximum and minimum precipitation intensity is shown in Figure 4. At the peak intensity the angular distribution becomes isotropic or slightly field-aligned over the downgoing hemisphere.

Generally the flux changes are ascribed to modulation of the pitch angle scattering in the equatorial plane via Doppler shifted gyro resonance with whistler mode waves (see Kennel and Petschek, 1966; Johnstone, 1978, 1983). Recently, Romich and Deehr (1984) have shown a relationship between the pulsation period and the intensity of the ion precipitation. They also noted the duration of the pulses was relatively constant but that the time between pulses varied thus causing the period to vary. Several modulation mechanisms have been put forward (see Sandahl, 1984) but so far they all leave unanswered questions when compared to the observations.

The morning side discrete auroral arcs embedded in the diffuse precipitation generally do not show the monoenergetic peak in the electron precipitation that is associated with the nightside arcs (see Fig. 3 of Chiu et al., 1983). Thus the morning side auroral zone arcs are not due to potential drops. This has left the question of how the arc forms unanswered. Chiu et al. (1983b) attempted to answer this question by considering the spatial modulation of the plasma-sheet warm plasma density by the mirror instability. This is still a topic that could use some theoretical work. More observations of the character of electron precipitation in these particular morning side arcs would also be helpful.

Inverted-V type precipitation does occur, rarely, on the poleward edge of the morning side aurora. Questions remain as to whether these precipitations always map to the boundary layer of the plasma sheet or whether they are ever magnetosheath plasma (Hoffman and Lin, 1981; Chiu et al., 1985). These points are discussed in Section 2.5.

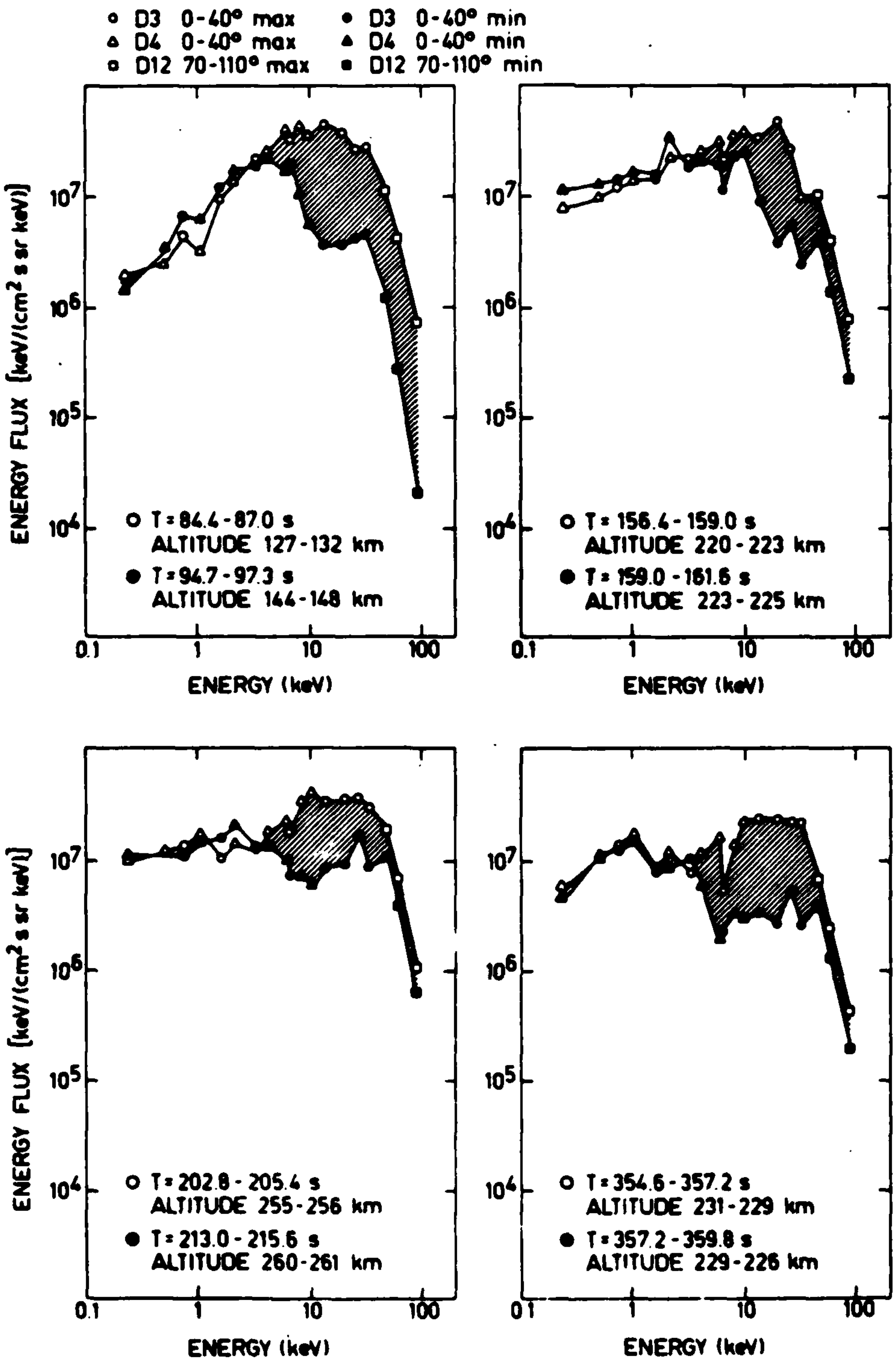

Figure 4. Electron Spectra Taken at Maximum and Minimum of a Pulsating Auroral Patch (after Sandahl, 1984).

2.4 DAYSIDE PRECIPITATION

The dayside electron precipitation can be identified as two general types: the soft cusp precipitation and the harder dayside auroral zone. The cusp electron precipitation coincides with a magnetosheath like ion precipitation and is generally found at higher latitudes than the dayside auroral zone (see Reiff, 1983; Fennell, 1985 and references therein). The cusp electron precipitation is intense and of relatively low energy (< 1 keV). The source of the cusp precipitation is generally stated to be the magnetosheath. The mechanisms for the plasma entry to the cusp have been described as direct entry on interconnected magnetosheath-magnetosphere field lines, diffusive entry and impulsive entry.

Using ion time of flight and dispersion effects the entry altitude has been estimated to be ~ 8-20 Re (see Burch et al., 1982; Reiff, 1983). There are also indications that the cusp ions are accelerated during entry to the cusp (Torbert and Carlson, 1980). The signature of the convection of plasma on cusp field lines has even been observed in the upflowing ion signatures (Chappell, 1984; Moore, 1985) and in the precipitating ion energy dispersion with latitude (Reiff et al., 1980). This latter signature is present when the IMF is southward and is expected in the 'open magnetosphere' model. During northward IMF the cusp ion access appears to be diffusive (Reiff et al., 1980).

The cusp electron precipitation is normally described as unaccelerated, isotropic and Maxwellian (Heikkila and Winningham, 1971; Frank and Ackerson, 1972; see also Frank, 1975 and references therein). Yet, there are observations which deviate from this picture. In particular, Zanetti et al. (1981) describe the occurrence of field-aligned electron distributions in the cusp. These distributions occurred in about half the cusp crossings and tended to lie near the equatorward edge. They did not appear to be consistent with acceleration by parallel electric fields (e.g., see Fig. 3 and Table 2 of Zanetti et al., 1981). While the authors discussed wave particle interactions as a possible mechanism for forming the field-aligned electron distributions, they came to no firm conclusions concerning such possibilities.

2.5 POLAR CAP ELECTRON PRECIPITATION

The latitudinal region above the auroral zone is the polar cap region. It is generally thought to be a region of open field lines which maps into the magnetotail lobes. Most of the time, a relatively structureless precipitation of low energy electrons, "polar rain" (Winningham and Heikkila, 1974), is observed in this region (see Gussenhoven et al., 1984 and references therein). The polar rain is usually weak (10^{-2} to 10^{-3} erg cm^{-2} s^{-1}) and soft (average energy $\lesssim$ 100 eV precipitation.) The relative intensity of the polar rain over the two polar caps is controlled by the Interplanetary Magnetic Field (IMF) direction. The precipitating electron intensity over the northern (southern) polar cap is greater than that over the southern (northern) polar cap for an antisunward (sunward) directed IMF (Mizera and Fennell, 1978; Gussenhoven, 1982). This combined with IMF control of the tail lobe fluxes (Yeager and Frank, 1976) lead to the conclusion that the polar rain was a component of the solar wind which gained unimpeded access to the tail lobes and polar caps (see Mizera and Fennell, 1978). The IMF control was related to the existence of an anisotropy of the solar wind electrons, or 'strahl'. This idea has been recently reinforced by Fairfield and Scudder (1985). They observed the 'strahl' electrons in the magnetotail lobes. The observed distributions were consistent with unimpeded and preferential entry of the strahl into the polar cap most directly connected magnetically to the sun. Figure 5 schematically shows this idea. Not everyone agrees with this picture of polar rain (Gussenhoven et al., 1984). It remains to examine the angular distributions of the polar rain in great detail to see if the weak pitch angle anisotropy (~ 5% at 1 Re) which is predicted in the strahl access picture is seen at lower altitude. DE-1 is probably the best platform for such a study.

More intense electron precipitation is also seen in the polar caps. Winningham and Heikkila (1974) called these "polar showers" and "polar squalls". Usually these structured precipitations are embedded in or near the boundaries of the polar rain. The peak precipitation can be relatively intense (~ 0.1 to 1 erg cm^{-2} s^{-1}) and have average energies of 100-200 eV. Hardy (1984) has studied these precipitations and found that they occur predominantly during positive IMF B_Z. This kind of relationship has also been noted for the high latitude and polar arcs, which are also often sun aligned (Gussenhoven, 1982 and references therein). These sun aligned polar arcs are relatively rare (~ 1% occurrence probability) and occur most often during magnetic quiescence (Ismail et al., 1977).

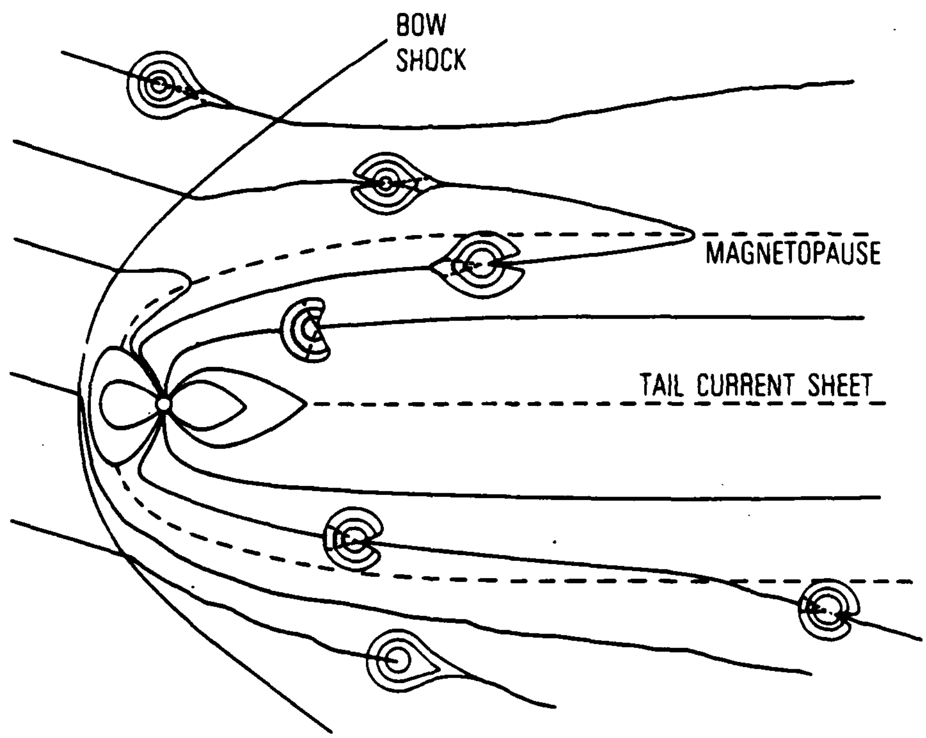

Figure 5. Illustration Showing Electron Distributions in Various Regions Near and in the Earth's Magnetosphere (after Fairfield and Scudder, 1985).

Examination of the electron precipitation over the sun aligned arcs has shown that the electrons have been accelerated by potential drops (see Fig. 4 of Murphree et al., 1983; Meng, 1981b). Chiu and Gorney (1983) find that the polar arcs have the same formation processes as the evening discrete arcs. Murphree et al. (1983) suggest that the polar rain particles have been accelerated to a few hundred eV to generate the arc precipitation. Meng (1981b) first suggested these were arcs on the poleward edge of the expanded, quiet auroral oval. Recently, Makita and Meng (1984) have stated that the source region for these quiet time arcs is not completely understood. They argue that near the dayside it may be the low latitude boundary layer plasma and at midnight the boundary plasma sheet plasma.

Frank et al. (1982) have reported the observation of a polar arc which extends from the nightside oval to the midday auroral zone. They have called this a Θ aurora. The precipitating electrons associated with this aurora are similar to those of the oval arcs (see Plate 2 and Fig. 3 of Frank et al., 1982). They argue this feature may result from a two cell convection in the polar cap and might require a bifurcation of the magnetotail lobe. Peterson and Shelley (1984) used the ion composition data in an attempt to distinguish the source plasma for the Θ aurora. While their results provide strong support for the idea that the arc occurs on field lines closing through the distant plasma sheet or plasma sheet boundary layer, it does not substantiate either the model of a bifurcated magnetotail or the expanded oval with an arc at the poleward edge. Thus the discussion of source plasma for the sun aligned polar arcs and the corresponding magnetospheric topology is not yet complete.

2.6 LOW ENERGY FIELD-ALIGNED ELECTRON DISTRIBUTIONS

Narrowly collimated field-aligned electron distributions at relatively low energies (< 500 eV) have been observed throughout the auroral regions. These distributions are usually to be distinguished from the electron beam associated with inverted-Vs which is field aligned only at energies near the peak of the precipitating electron spectrum. Here we are referring to upgoing, downgoing and counter-streaming field aligned electrons which generally have soft monotonic spectra (Fennell et al., 1979; Sharp et al., 1980; Klumpar, 1981; Collin et al., 1982; Lin et al., 1982, 1984a and references therein). The counter streaming electrons are least understood. They have been observed at middle altitudes (Lin et al., 1982, 1984a) and at the equator (Richardson et al., 1981 and references therein). Figure 2b (upper panel) is an example of counter streaming electrons in the auroral region.

The upflowing electron beams are often observed at the low latitude edge of inverted-Vs, and as part of the Region I Birkeland current (Klumpar, 1981; Burch et al., 1983; Gorney et al., 1985 and references therein). An example of upflowing electrons is shown in Figure 6. Often these upflowing electron beams are associated with the conic ion beams (see Section 2.1 and Gorney et al., 1985). Generally, these upflowing electrons have been accelerated through relatively small ($\lesssim$ tens of eV) potential drops. Also, the probability of observing these beams with existing instruments increases with increasing altitude, up to ~ 6000 km (Collin et al., 1982). This would indicate an extended potential drop. The evidence for the potential drops has come from analysis of the distribution functions of the electrons (Klumpar and Heikkila, 1982; Burch et al., 1983) or both electrons and ions (Gorney et al., 1985). At this point, no direct measurement of a downward electric field has been made although Mozer (1980) has inferred its existence from the measurements of the perpendicular electric field.

Downward electron beams are observed almost uniformly in altitude over the range 3000-8000 km and occur more frequently than upstreaming electrons (Collin et al., 1982). The limited DE-1 observations indicate that when the plasma current measured by plasma instruments is compared to the current measured by the magnetometer that they agree. When the component carried by the low energy beams is compared to the total, it is found that these beams can carry as much as 40 to 50% of the total current, when they occur. Generally, the beams are capable of carrying a more significant fraction of the downward current (Lin et al., 1984a).

The counter streaming electrons observed in the auroral regions have been classified into two types by Lin et al. (1982). Type 1 are those associated with an isotopic high energy ($\gtrsim$ 1 keV) precipitating electron population. They generally have a two component Maxwellian distribution function and are fairly stable, existing over a small spatial region. The type 1 may involve wave particle interactions (Lin et al., 1982). Type 2 counter streaming electrons are beams parallel and antiparallel to the magnetic field. They are

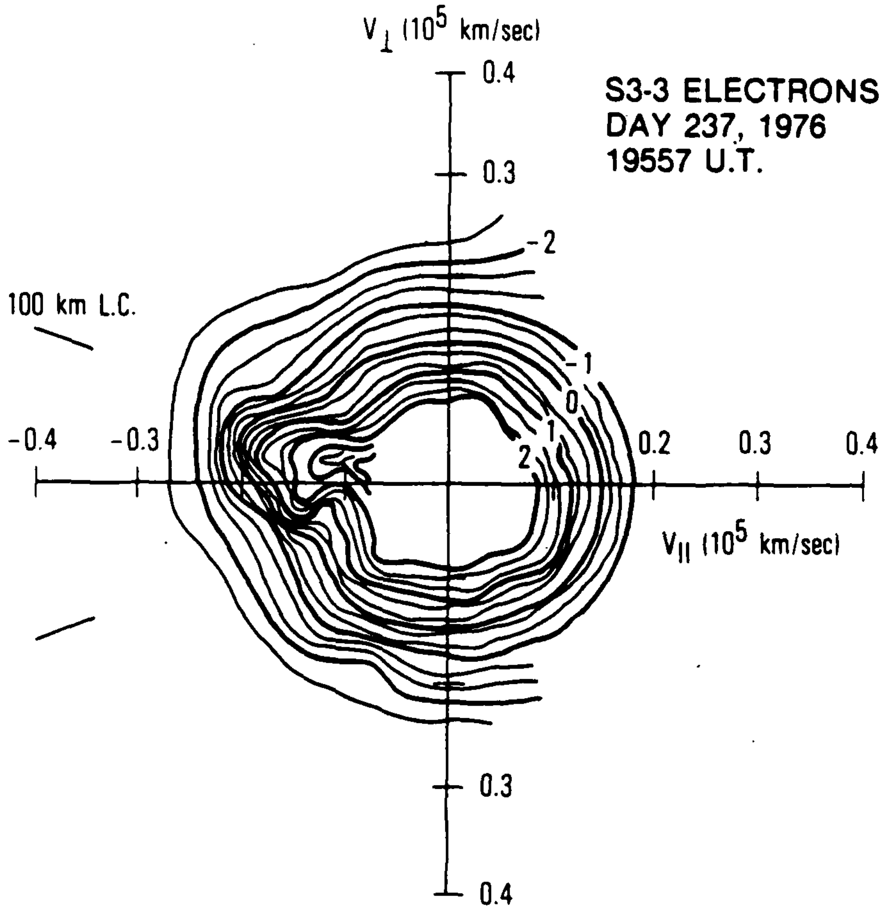

Figure 6. Upflowing Electron Distribution Observed on the S3-3 Satellite. This distribution was observed simultaneously with a conic ion distribution (after Gorney et al., 1985).

transient and possibly consistent with acceleration and trapping by parallel electric fields. Ion conics are often observed with the counter streaming electrons by the S3-3 satellite (Sharp et al., 1980). At the geomagnetic equator the counter streaming electrons are always associated with field-aligned ion distributions (see Fig. 1 of Richardson et al., 1981). At this point, the generation mechanisms for these counter streaming electrons is not totally clear.

3. IONOSPHERIC ION OUTFLOW

3.1 CONICS

Over the past several years it has become clear that ionospheric ions are often a major source of the plasmasheet and magnetospheric plasma. It has also become clear that transverse energization of these ions at varying altitudes plays a major role in their being supplied to the outer magnetosphere with significant energies and fluences (Chiu et al., 1983, 1984; Rosner et al., 1984 and references therein). Figure 2b (bottom panel) shows a distribution function for ions that have undergone transverse energization. This kind of distribution has been called an ion conic.

The transverse energization of ions on high latitude field lines has been observed from a few hundred kilometers (Wahlen et al., 1978; Yau et al., 1983) to 18,000 kilometers (Klumpar et al., 1984; Yau et al., 1984; Winningham and Burch, 1985) altitude on auroral field lines and even in the far magnetotail (Sharp et al., 1981, 1983). Initially, it was thought that the transverse acceleration occurred predominantly below a few thousand kilometers (Gorney et al., 1981) and on separate flux tubes from regions of parallel acceleration of ions (Cattell et al., 1979; Gorney et al., 1981).

The upward flowing "ion beams" (see below) had a perpendicular temperature greater than the temperature of the ions in the regions where parallel electric fields were known to exist. Thus, it appears a mass selective acceleration process is acting.

Recently, Klumpar et al. (1984) and Winningham and Burch (1985) have observed ion distributions which clearly show the effects of both parallel and transverse to B accelerations in the process of being transported upwards into the magnetosphere (see Fig. 7). The parallel acceleration signature was consistent with an inverted-V structure, indicating both types of acceleration can occur throughout the auroral zone. Similar observations have been made at low altitudes (few x 10^3 km) with transverse heating of thermal and suprathermal ions being clearly associated with O^+ outflows (Chappell, 1984; Lockwood et al., 1984; Moore et al., 1985). These latter data showed that the transverse heating can involve the entire thermal plasma to the point that ion "ring or "torus" distributions are generated. These transversely heated ion outflows occur in low density ($n < 100$ cm^{-3}) regions.

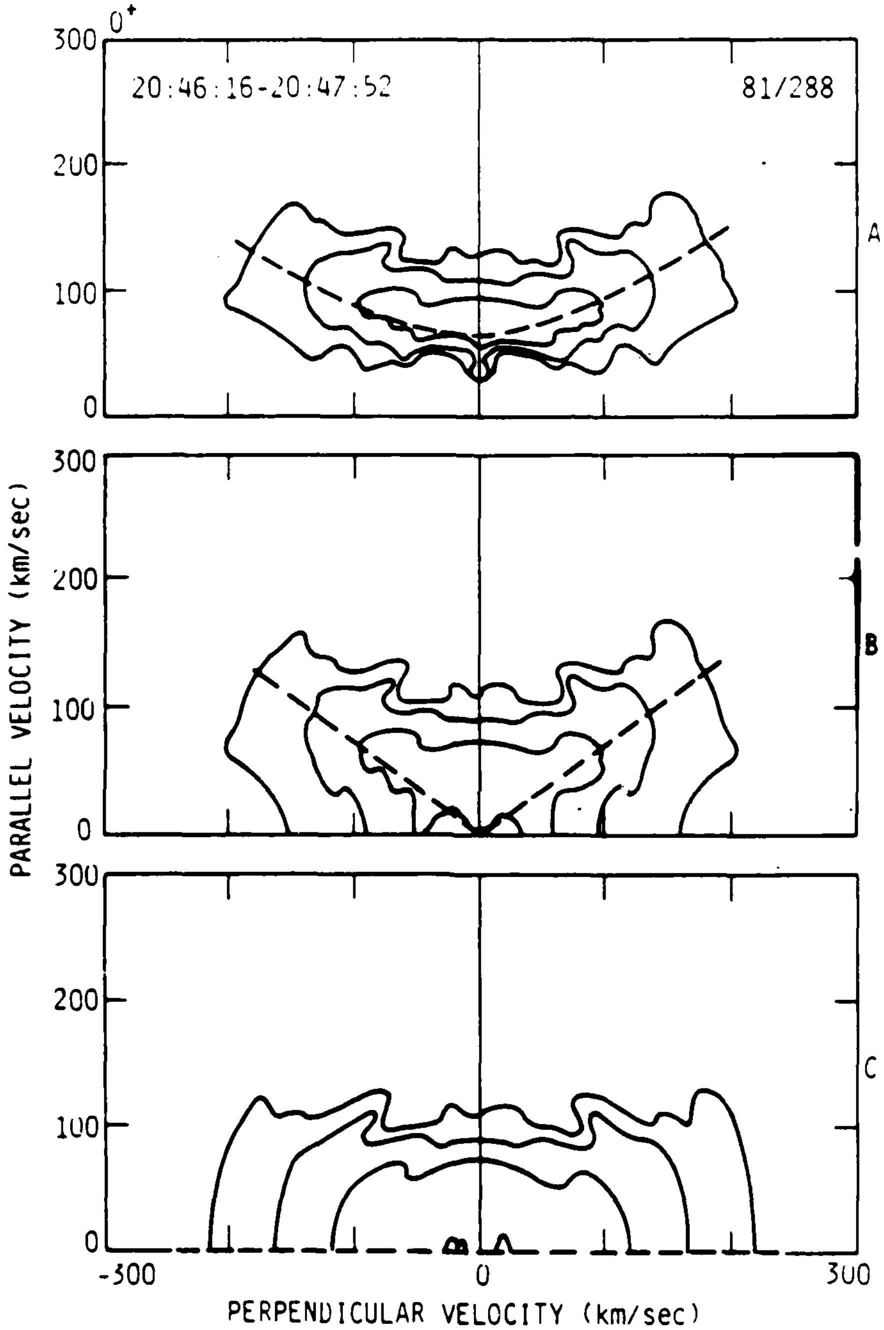

Figure 7. Oxygen Ion Distribution Function from DE-1 on 15 October 1981. The three panels show: (A) measured distribution; (b) distribution transformed through 310 V potential drop; and (C) distribution (B) adiabatically transformed to region where magnetic field intensity is a factor of 1.49 that at the satellite (after Klumpar et al., 1984).

In the dayside auroral region the suprathermal ion source appears as a field aligned flow dispersed tailward across the polar cap by the convective flow as sketched in Fig. 8 (Horwitz, 1984). On the nightside the ion beams are often bounded by ion conics with the cone angle increasing with distance from the beam region (see Moore et al., 1985).

The combination of these results leaves us with the impression that the nightside ion acceleration may go through multiple stages of transverse and parallel acceleration starting with transverse acceleration at ionospheric altitudes and passing into parallel and transverse acceleration at different points up the field line. We also see that the ion transport is affected by the convection electric fields such that the ions are dispersed throughout the polar region on tail lobe and plasma sheet field lines (Horwitz, 1984).

Examination of disturbed time data, from polar orbiting satellites, shows that conics are seen throughout the central plasma sheet (Fennell, 1985; Winningham and Burch, 1985) down to the plasma pause. The transverse acceleration of ions has also been observed near the outer regions of the plasmasphere at the geomagnetic equator (see Horwitz, 1980, 1982; and references therein). When measurements are made with high angular resolution and down to very low (< 10 eV) energies, then the combined transverse energization and net parallel and perpendicular drifts can be separated (Winningham and Burch, 1985).

In rare instances it appears that the accelerated upflowing ions are capable of carrying significant current. For example, Hellis and Winningham (1984) have reported a DE-2 observation of upward thermal ion fluxes as high as 10^{10} cm^{-2} sec^{-1} at the edges of inverted-V events. The upwards field aligned currents were 100 μ A m^{-2} with the upgoing ions contributing more than 10 μ A m^{-2} and at times currents comparable to the observed field aligned current. The observations were made at 900 km near the ionosphere-magnetosphere interface region and may be unique to this region in very disturbed times.

A recent statistical study at 8-23 x 10^3 km altitude by Yau et al. (1984) has shown that the upflowing ions occur more frequently near the equatorward edge of the oval and have higher energies there. At these altitudes the conic ions occurrence shows a dawn-dusk asymmetry favoring the dusk sector. The occurrence frequency of O^+ conics decreases with altitude relative to H^+

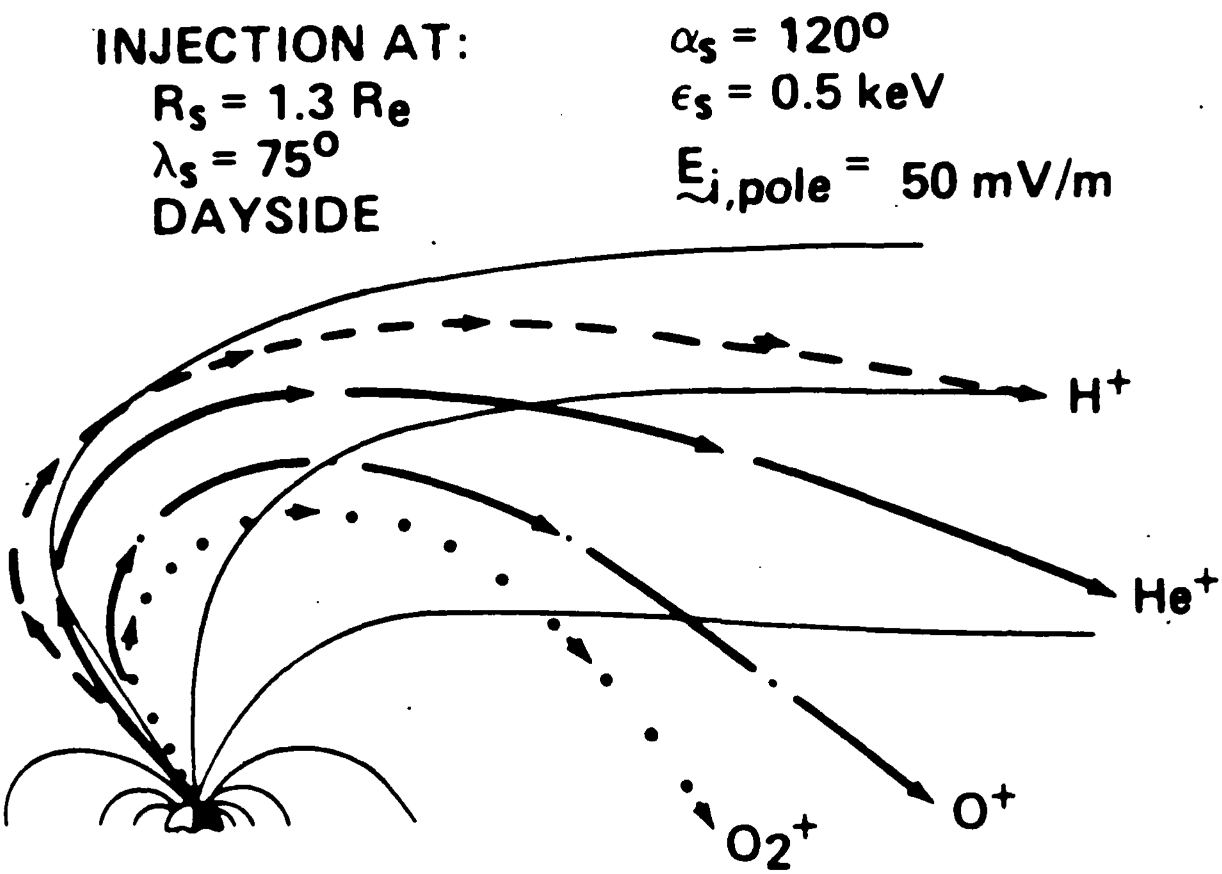

Figure 8. Trajectories of Upflowing Ions in the Polar Magnetosphere (after Horwitz, 1984).

conics. In the polar cap the upflowing ions are of relatively low energy but the outflow rates are significant, ranging from 2-3 x 10^{-24} s^{-1} to 3-10 x 10^{24} s^{-1} for quiet and disturbed periods, respectively.

The overall impression that transverse energization of ionospheric ions is a fundamental process occurring throughout the higher latitude regions where significant currents are flowing is succinctly stated in a paper by Winningham and Burch (1985). These authors state, "it is possible that conics represent a very natural.....state of the magnetosphere...As such they are a part of a more generalized polar wind and should be theoretically treated in a more realistic, expanded polar wind theory." This seems to represent our current understanding very nicely.

3.2 BEAMS

The term "ion beam" has been used by the S3-3 experimenters and some others to distinguish upflowing ion distributions which show indications of acceleration by a potential drop below the observation point (i.e., a peak in $f(v_\parallel)$. The statistical distribution of these upflowing ion beams shows a preference for the nightside auroral zones and inverted V regions (see Gorney et al., 1981; Yau et al., 1984 and references therein) as the regions where ion beams are seen. As discussed above, the artificial separation of upflowing ions into beams and conics may be breaking down as observations push to lower energy. Nevertheless, the existence of ion beams as defined here, no matter how low their energy, indicate that field-aligned potential drops exist on the flux tubes which map to their remote source point. They can be used to provide information about physical mechanisms which cause ion outlfow, but they must be interpreted carefully.

The altitudinal distribution of the upflowing ion beams (Ghielmetti et al., 1978; Gorney et al., 1981; Yau et al., 1984) has been used to predict the lower bound of the potential drop associated with inverted-V events and electrostatic shocks. This is generally quoted as 3000-4000 km. This lower bound depends somewhat on the threshold energy used to define the ion beams, although the results for a 90 eV and a 500 eV threshold are nearly identical (Ghielmetti et al., 1978; Gorney et al., 1981; Collin et al., 1981).

Downward flowing ion beams have rarely been observed by the S3-3 satellite (Fennell et al., 1979; Ghielmetti et al., 1979). At the equator

(Richardson et al., 1981; Olsen, 1982 and references therein) and in the high altitude magnetosphere (Lundin et al., 1982) field-aligned ion beams are observed fairly often during magnetically disturbed periods. Recently, downward flowing ion beams have been observed on DE (Winningham et al., 1984). These have been interpreted in terms of the convection electric field acting on ions flowing out from the ionosphere in the opposite hemisphere. The latitudinal (L-shell) displacement caused by inward convection acts as a 'velocity-filter' separating the different ion energies and species. Thus, at the equator, at high altitudes and at the opposite hemisphere from the source, the ions would always appear as beams (i.e., peaked $f(v_{\parallel})$). Therefore, once the observing platform is far enough from the source/acceleration region that the convection electric field plays a significant role in forming the observed ion f(v) (i.e., see Fig. 5 of Winningham and Burch, 1985), the ion beams must be carefully interpreted. These kinds of studies are just beginning to occur.

3.3 POLAR WIND

The escape of thermal ions from the ionosphere along field lines outside the plasmasphere has been predicted by theory and inferred from density measurements for some time (see Reiff, 1983 and references therein). The flow on closed field lines outside the plasmasphere exists because of the dynamic emptying and refilling which occurs there in response to magnetic activity and magnetospheric convection. The outer part of the magnetosphere contains flux tubes which open into the magnetotail. On these open field lines the polar wind becomes a source of ions for the plasma sheet or loses ions to the interplanetary medium. (See reviews by Horwitz, 1982 and Young, 1983 and references therein.) We will discuss here only those results pertaining to the auroral oval and polar cap regions.

Direct measurements of the upward flowing thermal ions, that make up the polar wind, were only recently made (Hoffman and Dodson, 1980; Gurgiolo and Burch, 1982). The initial DE satellite results showed that a heated and unheated component of the polar wind could be observed. They also showed that the average energy of the upflowing ions was higher than theoretically expected, and that the accelerated component of the polar wind was observed on each polar cap traversal (Chappell et al., 1982; Gurgiolo and Burch, 1982). It was also noted that the polar cap photoelectrons showed anomalous distributions indicative of a parallel electric field which could provide the polar wind ions escape energy (see Fig. 2 of Winningham and Gurgiolo, 1982).

More recently, it has been shown that the polar wind is supersonic with an average Mach number of 3, corresponding to a flow velocity of 16-25 km/sec (Nagai et al., 1984). The H^+ flow matched classical polar wind theory. Thus, we know that the light ion component of the polar wind is supersonic. We also know that a large fraction, if not all, of the time, the polar regions experience significant ion heating and acceleration sufficient for the heated ions, both light and heavy, to obtain escape velocity.

4. SUMMARY

We see that the electron and ion acceleration by parallel electric fields is substantiated for the inverted-V precipitation regions and many discrete arcs. The detailed processes by which the potential drops are generated are still being discussed. There is some evidence that the discrete arcs may be associated with electrostatic shocks, except in the dawn oval. We also see that pitch angle diffusion is still a good explanation for the diffuse aurora but the existing models may need some refinements of detail. The polar cap precipitation is still an area where much work needs to be done to define the source plasmas for the polar arcs, especially for IMF $B_z > 0$. The polar rain appears to be of solar origin, although there is not a consensus on this point. The dawn side discrete oval arcs have not been studied very well at this point. These arcs plus the pulsating aurora precipitation are still topics for fruitful research both observationally and theoretically.

The ion outflow studies have been most fruitful in the last decade. We now know that transverse acceleration of ions is observed throughout the auroral zone and down to the plasmasphere. It appears that nearly all ionospheric ion outflow, other than the classic polar wind, has its origin in transverse acceleration which provides the escape energy (especially for oxygen). The transverse acceleration occurs most often in the downward current regions but is not restricted to these regions.

Once the ions leave the ionosphere they can be further accelerated either perpendicular or parallel to the magnetic field and they are transported in latitude in the combined magnetospheric electric and magnetic fields. Thus, the ionospheric ions are transported throughout the outer magnetosphere.

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